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E. Zwicker

1. Introduction

The loudness or the intensity level of an arbitrary sound can be determined from the physically measurable sound quantities only if the laws by which the hearing organs develop loudness are known. Two important sound values are the band width with respect to the spectrum and the temporal structure. The dependence of loudness on each of these values individually has often been studied. This work is concerned with the interaction of these values; that is, with the development of loudness when both the spectrum and the temporal structure change. / 16*

The dependence of the loudness of a continuous sound on the spectrum has been studied by various authors [1, 2, 3, 4]. They agree in explaining that individual spectral portions of the bandwidth of the frequency groups generate partial loudnesses, the sum of which gives the total loudness, with consideration for the mutual repression. This property of the ear to divide the spectrum into individual regions, the frequency groups, was found not only with continuous sounds but also with sound pulses of different bandwidths [5]. With the assumption that an excitation distribution across the tonality forms from the spectrum and that the integral across the specific loudness thus derived

* Numbers in the margin indicate the pagination in the original foreign text.

gives the total loudness, it was possible to describe the measured dependences very well [6, 7], so that the effect of the spectrum on the loudness can be considered known. / 17

In comparison, the dependence of the loudness on the temporal structure of the sound, especially on the pulse duration and the pulse rate, is not quite so unambiguously explained. This is mostly because the results found in Dresden and widely published [8, 9, 10, 11, 12] cannot be made to agree with the reports of other authors [13, 14, 15, 16, 17, 18] having results which practically coincide among each other. There is agreement, however, that the development of loudness from pulses by the ear can be described in a simplified manner as if the sound intensity were observed through an RC element with a time constant and the resulting maximum value evaluated for loudness development as for continuous sounds. But while publications from Dresden have reported time constants of 23 ms to 30 ms, with a mean of 25 ms, as useful values (recently, to be sure, larger values of up to 50 ms have also been published [19, 20]), the other authors have found values between 70 ms and 200 ms, with an average of some 100 ms. So far, it has not been possible to explain this discrepancy. Measurements from other research groups have not been able to provide useful contributions here.

In this work, the dependence of loudness on both the spectrum and the time function have been remeasured with a group of six test subjects. In contrast to the previous studies mentioned, sounds were also used which had a spectral as well as a temporal structure. Figure 1 may clarify this. Time is shown toward the rear, with frequency on the horizontal axis. In the left drawing a sound is represented schematically. It is characterized principally by its spectrum. It could also have a long or short duration. The middle drawing represents a narrow-band sound characterized primarily by a particular time function. It could

Figure 1. Sounds with primarily spectral structure (left), temporal structure (center), and both spectral and temporal structure (right).

also be wide-banded. Finally, the right drawing shows a sound which has both temporal and spectral structure. This may serve as an example for the sound used later. The pulses could also have different bandwidths, or the could occur partially simultaneously and partially sequentially. If the individual sound components in Figure 1 are taken as tone pulses, then the left drawing represents five tone pulses of different frequencies presented simultaneously. The center drawing represents five tone pulses of the same frequency presented sequentially. The right drawing represents five tone pulses of different frequencies presented sequentially.

The experimental program includes three different segments, corresponding to the three characteristics of Figure 1. In the first segment, using the six subjects (who were the same for all loudness comparisons) we checked the extent to which the assumption that, in the state of building up, the integral of the specific loudness across the tonality gives the total loudness, is correct. The second experimental segment is intended to contribute to a clarification of the value of the time constant. It is also intended to establish whether the law of integration of the sound intensity over the duration still applies even with extreme time functions, such as rapid buildup and decay. In the third segment, finally, we describe experiments with sounds having both spectral and temporal structure, from which we shall learn whether and how the ear simultaneously integrates over the tonality and the duration.

The spectral components of the sound are formed from tones of 1 kHz, 1.35 kHz, 1.85 kHz, 2.5 kHz and 3.4 kHz. They are all two frequency groups apart in frequency. That is, they are separated by 2 Barks in tonality. Durations of 100 ms, 20 ms and 5 ms as well as a pulse sequence of five pulses, each of 5 ms duration with 15 ms interval, were used as time functions. In evaluation of the results it would have been desirable to adjust the levels of the individual tones so that each tone would produce the same loudness by itself. But because the curves of equal loudness are different for different subjects, this would have been very difficult to do. In all experiments, therefore, the levels of the individual tones were made the same. This adjustment has, at the same time, the advantage of simple and reliable testing. In the evaluation, however, it must be considered for part of the results that the individual tones are not equally loud.

The loudness comparisons were made binaurally by the method of swinging compensation [7]. A compensated dynamic earphone [7] was used as the electroacoustic transducer. The loudnesses were all measured twice – test and comparison sounds exchanged – so that each of the sounds to be compared could be changed once by the subject.

2. Summation Over the Tonality

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In a preliminary experiment, loudness comparisons were carried out between the 1.85 kHz tone and the other tones at pulse intensities, L, of 30 dB, 50 dB and 70 dB and at a pulse duration, t_i, of 100 ms. The result is shown in the four diagrams of Figure 2. The ordinate is the pulse intensity, $L_{1.85\ kHz}$, of the equally loud 1.85 kHz tones. The abscissa is the pulse intensity of the other tones. In order to save space, the individual diagrams are displaced so that the results can be separated clearly from each other. For clarity, the frequency of the tone matching the abscissa scale is shown on the curves. The measurements are presented as means with the probable deviations. The solid lines show the curves found, based on the measurements and fitted visually.

The results show that the 1.85 kHz tone produces the least loudness, because according to Figure 2, the subjects, on the average, set a higher intensity for the 1.85 kHz tone for equal loudness than for the other tones. All the measured curves in the four diagrams lie above the medians. The loudness-tonality diagrams obtained at a tone intensity of 50 dB, if a loudness level of 50 phon is taken for the 1 kHz tone and the loudness levels of the other tones are recalculated corresponding to the measurements shown in Figure 2, are plotted in Figure 3 [7]. According to this, the specific loudness, N', in Figure 3 has the smallest value for the 1.85 kHz tone, while the values are higher for the other tones. "Ideal" subjects would give almost the same specific loudness for all tones in the frequency range used. That is, the tones would be equally loud at the same intensity. A randomly composed group of subjects will always diverge from the "ideal" condition. The deviations measured in Figure 2 and presented in Figure 3 are not unusual. But it is necessary to take their presence into account in the calculations.

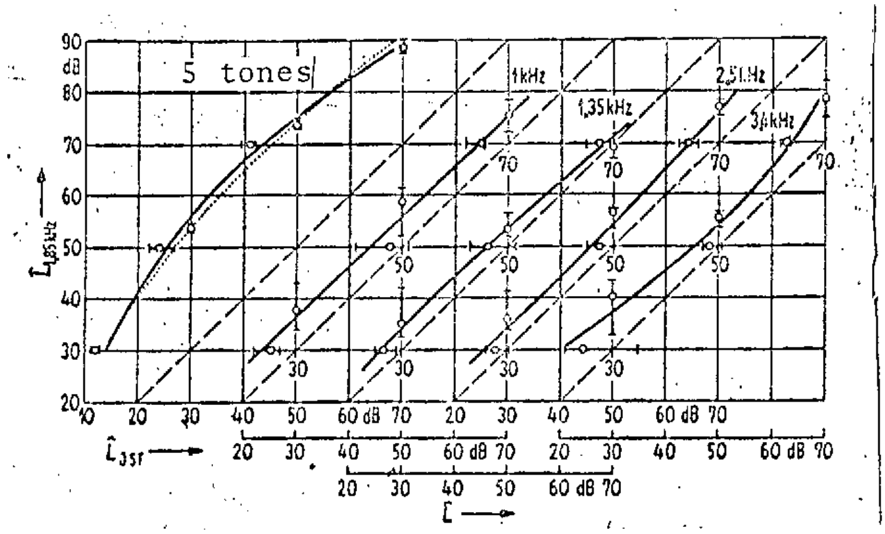

Figure 2. Results of the loudness comparisons between the 1.85 kHz tone and the 1 kHz, 1.35 kHz, 2.5 kHz and 3.4 kHz tones (four right diagrams) as well as the five tones presented jointly (left diagram). Duration of presentation 100 ms. The levels adjusted for equal loudness are shown as averages with probable deviations. The ordinate is the intensity $\hat{L}_{1.85\ \mathrm{kHz}}$ required for equal loudness, from which the 1.85 kHz tone pulse is cut out. The abscissa is the corresponding intensity L of the individual comparison tones (four right diagrams). For the left diagram, likewise, the intensity $\hat{L}_{J5T}$ for each of the five tones is presented as the abscissa. To save space the diagrams are displaced into each other so that the results can still be distinctly assigned to the abscissa values. The solid curves are determined visually. The dotted curves show the calculated values.

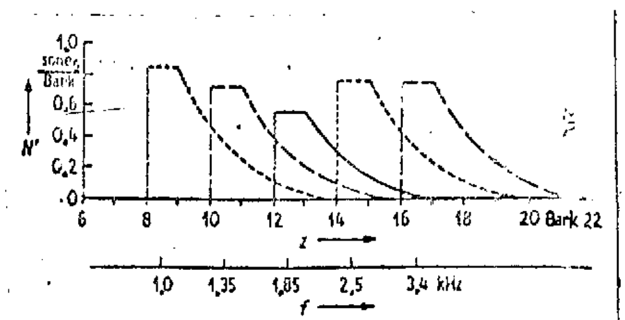

Figure 3. Loudness-tonality diagrams for the five different tones at a level of 50 dB for each tone, determined from the measurements of Figure 2.

This can be done easily using the loudness-tonality diagram (cf. Figure 3). /19

The loudness of the five tones presented jointly was measured after this preliminary experiment. It is a measure for the loudness summation across the tonality. The results from this experiment are shown at the far left in Figure 2. The intensity of the equally loud 1.85 kHz tone is shown as a function of the intensity $L_{[illegible]}$ of each individual one of the five tones presented simultaneously. The solid line shows the curve fitted visually to the measured averages. From the loudness comparison measurements of the individual tones (Figure 2, the four right curves) we can calculate the total loudness of the five-tone mixture at all intensities, if the loudness-tonality diagram according to Figure 3 is noted. As the areas under the defined curves yield the loudness, we must, for the total loudness of the five-tone mixture, determine only the total area under the five defined curves for the five tones, with the areas covered more than once taken into consideration only once. The calculations were done by this method, and their results are plotted as the left dotted curve in Figure 2.

The agreement between measurement and calculation is very good. This can be considered as confirmation that the specific loudness N' is summed across the tonality in the way it is done in the calculation method [7], with areas covered multiply evaluated only once, to form the loudness, N.

3. Summation Over the Time

The differences in the time constants used to describe the dynamic properties of the ear in development of loudness, which were mentioned in the introduction, can be tested only by more measurements. Therefore, loudness comparisons were carried out

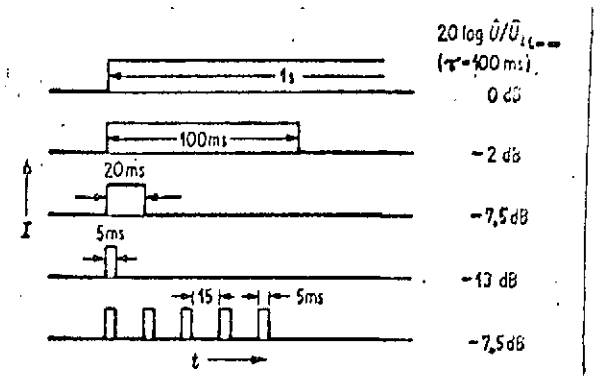

Figure 4. Time constants for sound used in the loudness comparisons. Shown at the left are statements of the expected level differences if the sound intensity is evaluated through an RC element with a time constant of 100 ms.

the four time functions shown in the lower part of Figure 4, none of which exceed a total duration of 100 ms. These comparisons were made both for single tones (narrow band) and for five tones simultaneously (broad band). Statements of the maximum voltages $\hat{U}$ at the output of an RC element (time constant $\tau = 100$ ms) which should correspond to the effective sound intensity are shown at the right side of Figure 4. The value shown is the logarithm, rounded to 0.5 dB, referred to the maximum value $\hat{U}_{t\to\infty}$ for a very long pulse. The level difference taken from Figure 4 can be considered directly as the level difference to be expected for the same loudness. Here it is presumed that a time constant of 100 ms is suitable for the sound intensity so as to be able to describe the dynamic properties of the ear in loudness development to a first approximation.

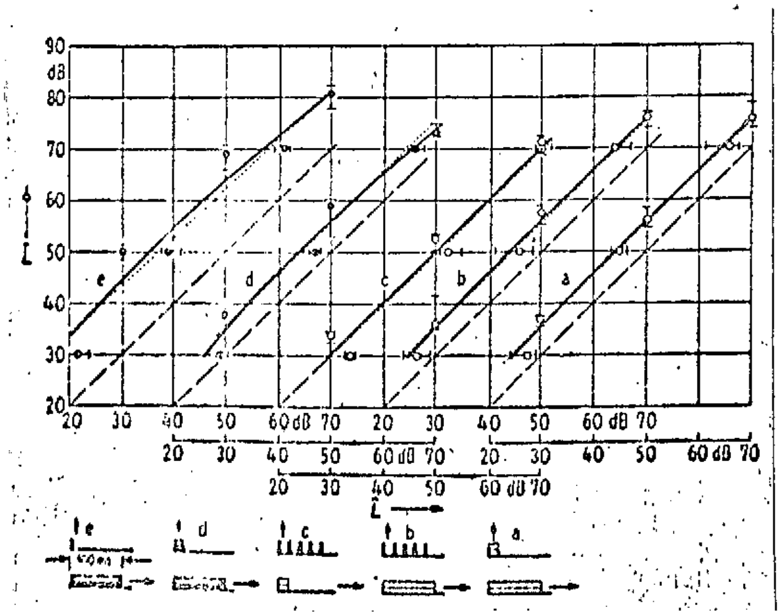

Figure 5. Results of the loudness comparison between sounds with different time functions. The drawings under the intersections with the axes characterize the time functions for the abscissas relative to the ordinates. The middle line designates the 1.85 kHz tone. The solid drawings or symbols designate five tones offered jointly. The abscissas and ordinates indicate the level L of the individual tones from which the pulses are taken. Solid curves: determined visually. Dotted curves: values to be expected from Figure 4.

The results of the loudness comparison by the six subjects are plotted as means, with probable deviation, in Figure 5. Here again, the abscissa scales are telescoped. The pulse levels of the individual tones are plotted both as abscissas and as ordinates. This is also the case when five tones are presented together. In Figure 5, bottom, the time and the spectral patterns of the comparison sounds matching the diagrams are plotted directly below the corresponding intersections of the axes. The drawings with a central dash indicate the use of one tone with the average frequency position of 1.85 kHz. The solid drawings characterize the broad-band sound of the five tones presented simultaneously.

Diagram 5a shows the result of the comparison between a 1.85 kHz tone pulse of 20 ms duration (ordinate) and one of 100 ms duration (abscissa). The solid curve is the average, plotted visually. The dotted curve corresponds to the values which would be expected on the assumption of a 100 ms time constant. According to Figure 4, right, the shift from the 45° line from the origin should be 7.5 dB - 2 dB = 5.5 dB. This matches the measurements exactly. On the assumption of a 25 ms time constant this difference is only 2 dB, which is not confirmed by the measurements.

Diagram 5b shows corresponding results. The pulse level of the 100 ms long 1.85 kHz tone pulse is plotted as the abscissa, and that of the pulse sequence of five tone pulses 5 ms long at intervals of 15 ms is plotted as the ordinate. The measurements show that the level of the pulse sequence must be set 5 dB to 6 dB higher (solid curve) in order to perceive the same loudness. This also agrees quite well with the values expected from Figure 4 (dotted line).

If the same measurement is repeated, but with the duration of the 100 ms long 1.85 kHz tone pulse reduced to 20 ms (abscissa), then results according to Figure 5c are found. The pulse levels must be set equally great if the two sounds are to be equally loud. The central curve lies on the 45° line from the origin. This measurement, too, can be interpreted with Figure 4. The maximum voltage appearing at the RC element with a time constant of 100 ms is equally great for both sounds if the pulse levels are the same, as is assumed in Figure 4.

Measurements obtained with simultaneous presentation of all five tones (broad-band sound) are plotted in Figures 5d and 5e. While a 20 ms pulse is compared with a 100 ms pulse in Figure 5d, a pulse of 5 ms is used in Figure 5e. Accordingly, the measurement for Figure 5d corresponds to that of Figure 5a, except that Figure 5d was measured with broad-band sound. The result is very similar, though, as the comparison between measurement (solid) and calculation (dotted) shows.

If the pulse duration is very considerably shortened to 5 ms, then the curvature of the loudness curve toward the threshold because of the reduction of the equivalent sound intensity by 13 dB - 2 dB = 11 dB must be considered in the calculation, especially for broad-band sounds (compare Figure 5e). At levels of 30 dB to 50 dB, then, the calculated curve (dotted) is more than 11 dB above the 45° line from the origin. The mean value of the measurements (solid) is described quite well by evaluation of the sound intensity through an RC element with a time constant of 100 ms here also. This is true for all the measurements shown in Figure 5, of which those of Figure 5a, 5d and 5e have particularly powerful predictive force. The assumption of a 25 ms time constant would not be able to describe these measurements satisfactorily.

The sounds used up to this point had symmetrical time functions with identical buildup and decay. In the following we shall investigate the influence of the buildup or decay on the loudness. This seems particularly necessary because the sound pulses which occur in practice almost all have unsymmetrical time functions. The loudness comparison was, then, extended to sounds which build up very rapidly and decay slowly (designated briefly as decaying) and to those which build up slowly and decay very rapidly (designated briefly as building up). Oscillograms of such sound pulses, taken from a 1.2 kHz tone, are shown in Figure 6.

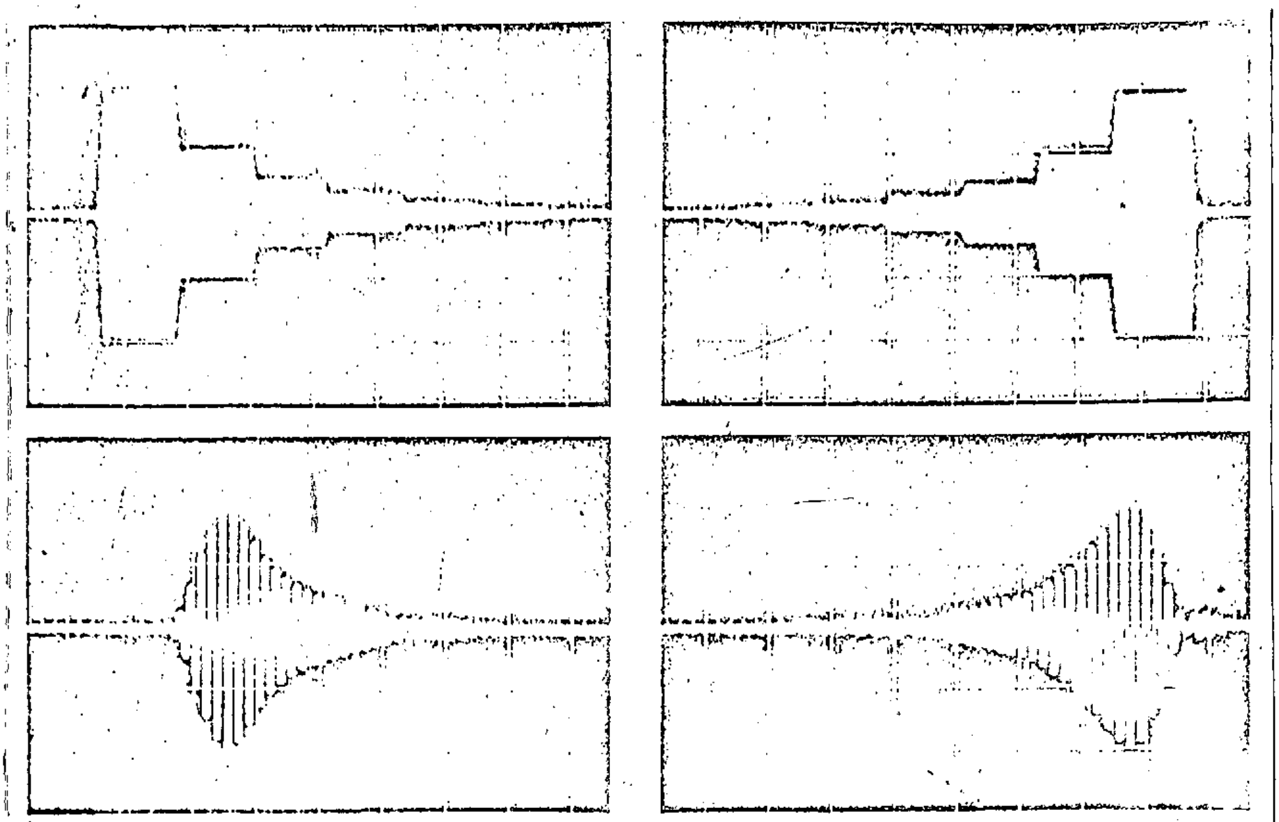

Figure 6. 1.2 kHz tone pulses with "opposing" time functions. Above: sequence of 6 50 ms pulses with levels increased and decreased by 6 dB, respectively. Below: same, with 5 ms pulses. The transitions are obscured because the pulses were led through third filters.
Abscissa scale: above: 50 ms/division; below: 5 ms/div.

The upper pair is composed of six sequential pulses of 1.2 kHz tone, each 60 ms long. The increase or decrease in level from pulse to pulse is 6 dB. In order to avoid any audible click at the switching points, the pulse sequences were led through third filters. While the upper pulse pair has a total duration of 6 · 60 ms = 360 ms, the total duration of the pulse pair shown in Figure 6, below, is only 6 · 5 ms = 30 ms. Here, the individual pulses are strongly obscured by the third filter. The time function shows only an even buildup or decay. The question of whether the building-up pulse sounds exactly like the decaying pulse was answered in a series of measurements /21 in which single pulses of 60 ms, 20 ms, 10 ms and 5 ms were used at maximum pulse levels of 30 dB, 50 dB, 70 dB and 90 dB. Pulses of the same total duration were always compared with each other. The test subject could change the building-up pulses in the first series of measurements, and the decaying ones in a second series. Table I shows the mean of these two measurements. In this relation,

Table I. LOUDNESS COMPARISON OF BUILDING-UP AND DECAYING PULSES. LEVEL DIFFERENCE ΔL REQUIRED AT IDENTICAL LOUDNESS.

Pulse level L_{max} of the largest single pulse dB	$\Delta L = L$ decaying with time − L rising with time			
	6 x 60 ms dB	6 x 20 ms dB	6 x 10 ms dB	6 x 5 ms dB
30	0	− 1	− 0,3	+ 1,5
50	+ 1,5	0	− 0,3	+ 1,0
70	0	− 1,5	0	± 0,5
90	+ 2,0	− 0,3	+ 0,3	+ 0,3
Mean	+ 0,9	− 0,7	− 0,1	+ 0,8

it did not seem necessary to present the individual measurements from the six subjects, as the deviations of the individual measurements and of the averages of the two series of measurements differed only slightly and were hardly systematic.

The interpolated means are summarized in Table 1. In general, it can be said that the building-up and decaying pulses are equally loud if the levels of the individual pulses from which they are composed are equal. This law appears to be followed very exactly because the deviations, as shown in Table I, do not exceed values of 2 dB and are not systematic. In the average, the deviation is only 0.3 dB. This result is quite surprisingly simple, if we consider the very complex processes which such pulse sequences initiate in the hearing organs, especially in the nerve paths. But it is quite compatible with the assumption that the maximum value of a sound intensity evaluated through an RC element with a time constant of 100 ms is, to a first approximation, the quantity which is decisive for loudness development.

Thus, we have tested and confirmed the law by which the hearing organs develop loudness, both for the addition of partial loudnesses over the tonality for continuous sounds and single pulses and for the incomplete integration (RC element) of sound intensity over the time for pulse sequences and other time functions. /22

4. Summation Over Tonality and Duration

In the following, we describe measurement results obtained by loudness comparisons with the same group of subjects, in which sounds with both temporal and spectral structure were used.

For this, we selected a sequence of 5 ms or 20 ms long, as sketched at the right in Figure 1. In order to avoid systematic error, the five individual pulses were not presented in the order of increasing frequency. Rather, the sequence 1.370 Hz, 2,500 Hz, 1,000 Hz, 3,400 Hz, 1,850 Hz was selected. This is shown in the drawings of the lower part of Figure 7 by

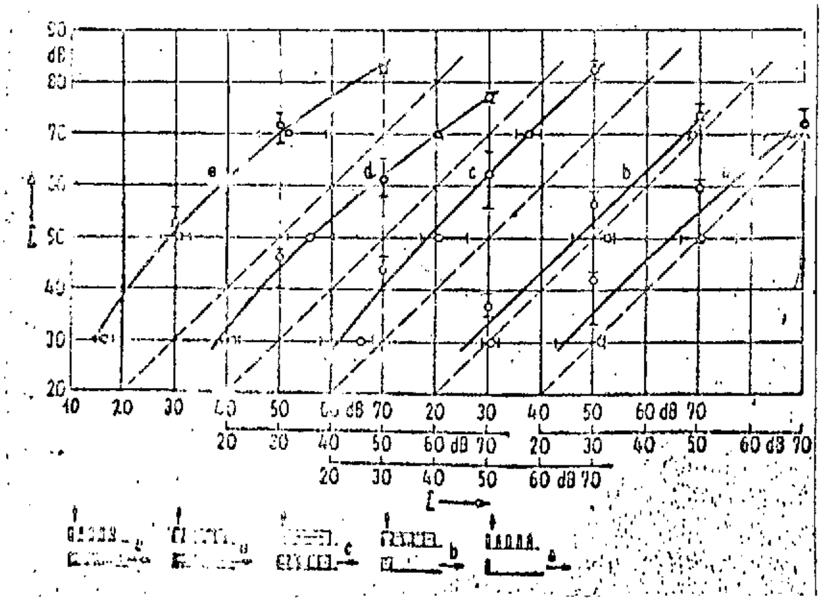

Figure 7. Results of loudness comparisons for sounds with both spectral and temporal structure. Presentation as in Figure 5. The drawings indicate the sounds used. (central line, 1.85 kHz; solid: five tones simultaneously; changing line height: tone sequence of 1.35 kHz, 2.5 kHz, 1 kHz, 3.4 kHz, 1.85 kHz).

shifting the height of the center line. As in the preceding measurements, two loudness comparisons were performed, so that each of the sounds to be compared could be changed once by the test subject. The diagrams, again, show the average value with the probable deviations.

The first two measurements were intended to clarify whether the five tone pulses are just as loud with simultaneous presentation as with sequential presentation, if the duration of the entire presentation does not exceed 100 ms. For this, we first compared a sequence of five tone pulses, 5 ms long, of the frequencies given above, at intervals of 15 ms, with a pulse made up of five tone pulses 5 ms long presented simultaneously. Figure 7, bottom, shows the sound spectrum and the time spectrum.

The results are shown in Diagram 7a. Again, the levels, L, of the individual tones (all five levels are identical) from which the pulses are taken, adjusted for the same loudness, are plotted. The abscissa is the level for simultaneous presentation and the ordinate is the level for sequential presentation.

The result in Figure 7a shows that the level for sequential presentation must be set higher by some 5 dB (low levels) to 3 dB (high levels) in order to have the same loudness. A similar result is obtained if the pulse lengths of the individual pulses are increased from 5 ms to 20 ms, at the expense of the intervals. The corresponding sounds are sketched in Figure 7b, bottom, and the results are shown in Diagram 7b. As in all curves, the solid line shows the mean value plotted visually. Here again, the level of the sequential pulses must be set higher, this time by 3 dB for all levels, to get the same loudness. This means that with the same levels for the partial tone pulses the pulses presented simultaneously are louder than those presented sequentially. This indicates that the ear integrates not only for a sequence of sounds from the same part of the spectrum (Figure 5) but also for a sequence of sounds from different parts of the spectrum, even though only partially. If no integration at all had occurred, i. e., if the loudness had been developed only from the individual sequential spectral portions, there would have had to have been a considerably greater difference. The difference in the result for five tones as compared to the results for the loudest individual tones can be made up from Figure 2. It amounts to some 23 dB - 7 dB = 16 dB. The measurements in Diagrams 7a and 7b are considerably below this value. / 23
Therefore, the assumption that no integration over time occurs at all provides a considerably poorer description of the result than does the assumption of complete integration. The actual results are intermediate and can best be described preliminarily by not quite complete integration.

In the loudness comparisons according to Sketches 7a and 7b, the total durations of both sounds were clearly different (5 ms as compared to 85 ms in Figure 7a; 20 ms as compared to 100 ms in Figure 7b). In the following three experiments, we attempted to avoid this difference largely, so as to exclude any possible undesired effects on the measurements. Diagram 7c shows results which appeared from comparison of a 100 ms long 1.85 kHz tone pulse with a pulse sequence of five 20 ms long tone pulses of different frequencies (cf. Sketch 7c). On the average, the level of the single tone pulse was set higher by 11 dB than the level of the tone pulse sequence, in order to get the same loudness. Assuming complete temporal integration, we can predict the result from the measurements of Figures 5a and 5d and Figure 2 for five tones. The expected difference must be, on the average, 23 dB - 6 dB = 17 dB. The missing 6 dB, as compared to the 11 dB, measured in Figure 7c must again be ascribed to the incomplete integration.

The measurements of Figures 7d and 7e show similar results. Five-tone pulses, 100 ms long, were compared with sequences of five single tone pulses of different frequency and 5 ms or 20 ms duration (compare Drawings 7d and 7e). The measurement for Figure 7d shows that the level, L of the single pulses (ordinate) must on the average be set 11 dB higher than the level of the five-tone pulse to get the same loudness. For complete integration, we would expect 6 dB from the measurement of Figure 5d. The remaining 5 dB must be ascribed to incomplete integration here also. The results are similar for the measurement in Figure 7e. There, a level difference averaging 19 dB was set for the same loudness, while a difference averaging 12 dB would be expected from Figure 5e.

All measurements performed with sounds having both spectral and temporal structure show results indicating that although complete summation of the loudness portions over tonality occurs, the summation of the loudness components over the duration of 100 ms is apparently incomplete. The question of what description is appropriate for such behavior is discussed below.

First we shall discuss the measuring accuracy with which these not entirely simple loudness comparisons were attained. For this, we find comparisons of the results of those measurements which can be closed up into a ring experiment. The measurements for Figure 7c and 7d, in comparison to the measurement for Figure 2 (five tones) are an example of this. The loudness of the tone pulse sequence in Figure 7c can be combined with the result from Figure 7d, so that we can get a satatement of the loudness of the 1.85 kHz tone pulse in comparison to that of the five-tone pulse. But this comparison has also been performed directly in measurement 2 (five tones). Quantitatively, we get an average of 11.5 dB from Figure 7c and 11.5 dB from Figure 7d. Both together agree well with the 23 dB which can be determined as an average from measurement 2 (five tones). The situation is similar for measurements for Figure 7a (4.5 dB), Figure 5e (12 dB) and Figure 7e (19 dB), as well as for the measurements for Figure 7b (3 dB), Figure 5d (6 dB) and Figure 7d (11.5 dB). Even if we deviate from the mean level differences and convert the individual results at discrete level values into each other, the deviations which appear are hardly larger. We can, accordingly, count on a measuring accuracy of ± 3 dB, even at these extreme loudness comparisons. No systematic deviations could be detected.

5. Discussion

The concepts previously known [4, 13, 16, 19] on the dynamic behavior of the ear in the development of loudness can be considered only as coarse approximations. To be sure, these approximations are of great practical utility, as, for example, the transformation of the time function of the sound intensity through an RC element with a time constant of 100 ms. But they do not lead to a deeper understanding of the processes occurring in the ear. Even if there is not to be any research on the information transfer going on, there should at least be attempts to extend and generalize concepts [7, 21] which have led to quite useful results.

For continuous sound (duration $\geqq$ 100 ms) the development of the loudness, N, from the loudness components, the so-called specific loudness, N', can be considered as a very useful model concept. In this case the individual spectral components are converted into sound intensities $I_{\Delta f_G}$ for each frequency group, /24 and the distribution of the specific loudness, N'(z) over the tonality, z, is determined from these. The total loudness, N, is derived from the integral

$$N = \int_0^{24\,\mathrm{Bark}} N' \, dz$$

In symbolic presentation, then, for continuous sound we have:

$$p = F(t) \rightarrow I_{\Delta f_G}(z) \rightarrow N'(z), \quad N = \int_0^{24\,\mathrm{Bark}} N'(z) \, dz .$$

For narrow-band or wide-band pulses, we can make use of the concept that the partial loudnesses reach a maximum value at the same time, so that we need not consider a time-dependent specific loudness, but need only make a statement about the occurrence of these maximum values. Evaluation of the sound intensity through an RC element (τ = 100 ms) and the further processing of the maximum value appearing at the RC element is an example of that. Presented symbolically, we have for pulses:

$$p = F(f,t) \rightarrow I_{\Delta f_G}(z,t) \rightarrow N'_{max}(z), \quad N = \int_0^{24\,\mathrm{Bark}} N'_{max}(z)\,dz.$$

For sounds with arbitrary time and spectral functions we can no longer retain the crude approximation which leads to a maximum value of the specific loudness, N'_{max}. In this case we must draw our conclusions from the time functions of the sound intensities across the time-dependent excitation distribution E(t,z) [7] occurring in the individual frequency groups for the specific loudness, N'(t,z), which depends both on the time, t, and on the tonality, z. The loudness, N(t), arises from the integral of the specific loudness, N'(t,z) only over z. It is time-dependent. In symbolic representation, then, we have for the general case:

$$p = F(t,f) \rightarrow I_{\Delta f_G}(t,z) \rightarrow E(t,z) \rightarrow N'(t,z); \quad N(t) = \int_0^{24\,\mathrm{Bark}} N'(t,z)\,dz.$$

For continuous sound (adaptation not considered), N(t) becomes independent of t. For pulses, only the maximum value, $N(t)_{max}$ is important.

Unfortunately, the relation between $I_{\Delta f_G}(t)$ and N'(t,z), which is necessary for the calculation, is not yet known. As already mentioned, we cannot consider the crude approximation (τ = 100 ms). The time function and the relation sought here must describe not only the loudness but also other properties, such as the dynamic behavior of the ear in developing the threshold. Qualitative evaluations cannot be performed until

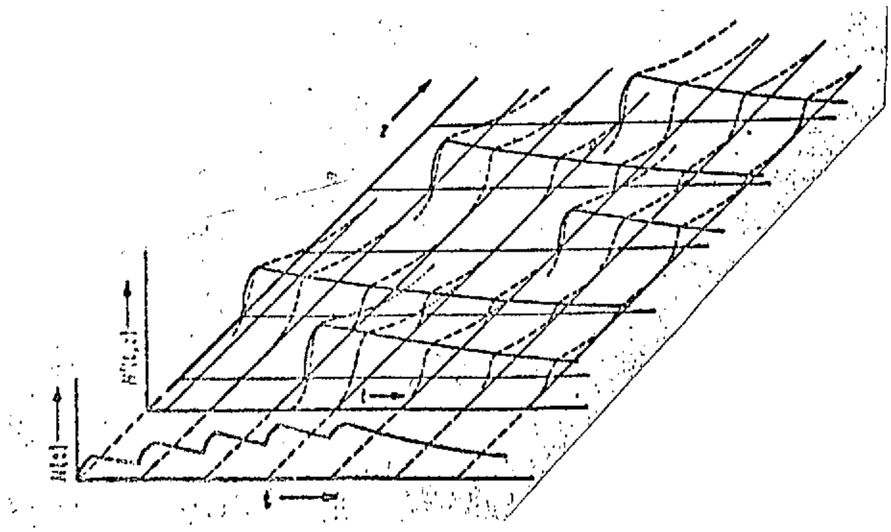

Figure 8. Drawing of a loudness-tonality-time diagram for a sequence of five relatively brief tone pulses with different frequencies. The specific loudness, N', is plotted as a function of the tonality, z, and of the time, t. In the lower portion, the matching loudness, N(t) is plotted as a function of the time.

the relation mentioned is investigated. A first attempt at clarification has been reported elsewhere [22].

Figure 8, however, shows, at least qualitatively, the type of concepts on which a general formula is based, and how the measurements can be described in essence with it. The loudness-tonality-time diagram for the tone pulse sequence of Figure 7a is shown qualitatively in Figure 8. The individual tone pulses produce rapidly rising specific loudnesses, N'(t,z) in the appropriate tonality ranges. These decay slowly [22]. The loudness, N(t) expressed by the integral $\int N'(t, z)dz$, will grow rapidly with each new pulse and then decay again (compare the sketch in Figure 8, bottom). If the succeeding pulse begins before the specific loudness of the preceding pulse has decayed, then the loudness, N(t) will not rise to a larger value, but the maximal values of the partial loudnesses will be only incompletely integrated because they have already partially decayed. If the partial loudnesses in Figure 8 are shifted toward each other in time, we get the representation in which the maximum values of the partial loudnesses coincide in time, corresponding to the five-tone pulse in the measurement of Figure 7a. It is easy to see that for such presentation the loudness /25

$$N(t) = \int N'(t, z)\, dz\,.$$

reaches a larger value, corresponding to the results shown in Diagram 7a.

I wish to thank my coworkers, who served as experimental subjects, for their cooperation.

REFERENCES

1. Zwicker, E. and R. Feldtkeller. On the Loudnesses of Noises of Equal Forms. Acustica, Vol. 5, 1955, p. 304.

2. Bauch, H. The Importance of the Frequency Group for the Loudness of Sounds. Acustica, Vol. 6, 1956, p. 40.

3. Zwicker, E., G. Flottorp and S.S. Stevens. Critical Band Width in Loudness Summation. J. Acoust. Soc. Amer., Vol. 29, 1957, p. 548.

4. Niese, H. Study on the Closed Representation of the Loudness Development Law for Arbitrarily Complex Noise Excitation. Hochfrequenztech. u. Elektroakust., Vol. 70, 1961, p. 51.

5. Port, E. Zur Lautstärke einzelner Rauschimpulse (Loudness of Single Noise Pulses). Proc. IVth Int. Congr. on Acoustics, Copenhagen, 1962.

6. Zwicker, E. and B. Scharf. A Model of Loudness Summation. Psych. Rev., Vol. 72, 1965, p. 3.

7. Zwicker, E. and R. Feldtkeller. Das Ohr als Nachrichtenempfänger (The Ear as a Communications Receptor). 2. erw. Aufl., S. Hirzel. Verlag, Stuttgart, 1967.

8. Niese, H. Investigation of the Sensation of Loudness from Rhythmic Noises. Hochfrequenztech. u. Elektroakust., Vol. 66, 1958, p. 115.

9. Niese, H. The Inertia of Loudness Development as a Function of the Sound Level. Hochfrequenztech. u. Elektroakust., Vol. 68, 1959, p. 143.

10. Niese, H. The Interaction of the Effects of Noise Bandwidth and Noise Time Function on the Loudness. Hochfrequenztech. u. Elektroakust., Vol. 70, 1961, p. 79.

11. Reichardt, W. and H. Niese. Addition of Sound Excitations in Individual Frequency Groups for Pulse Noises. Acoustica, Vol. 16, 1965-1966, p. 295.

12. Reichardt, W., H. Niese and M. Müller. The Unevenness Components of the Loudness of Pulses and Their Representation in a Pulse Sound Level Meter. Hochfrequenztech. u. Elektroakust., Vol. 75, 1966, p. 31.

13. Port, E. On the Sensation and Measurement of Loudness of Pulsatile Noises. Acustica, Vol. 13, 1963, Supplement, p. 224.

14. Zwicker, E. Temporal Effects in Simultaneous Masking by White-Noise Bursts. J. Acoust. Soc. Amer., Vol. 37, 1965, p. 653.

15. Stevens, J.C. and J.W. Hall. Brightness and Loudness as Function of Stimulus Duration. Perception and Psychophys., Vol. 1, 1966, p. 319.

16. Zwicker, E. A Contribution to Measurement of Loudness of Sounds Containing Pulses. Acustica, Vol. 17, 1966, p. 11.

17. Wright, H.N. Loudness as a Function of Duration. Paper at the 69th Meeting of Acoust. Soc. Amer., Washington, D.C., 1965.

18. Bauer, B.B. and E.L. Torick. Researches in Loudness Measurement. Paper at the Annual Convention of the National Association of Broadcasters, Chicago, 1966.

19. Reichardt, W. On the Inertia of Loudness Development. Acustica, Vol. 15, 1965, p. 236.

20. Notbohm, K. Determination of Aural Inertia by the Constancy Method. Hochfrequenztech. u. Elektroakust., Vol. 76, 1967, p. 165.

21. Zwicker, E. Über die Dynamik der Lautheit (On the Dynamics of Loudness). Proc. V. Int. Congr. on Acoustics, Liège, 1965.

22. Zwicker, E. A Model Describing Temporal Effects in Loudness and Threshold. 6th ICA Congress Tokyo, 1968.

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16. Abstract
Comparative measurements of loudness have been carried out with sound signals composed of five sound pulses of frequencies 1.0 kHz, 1.35 kHz, 1.85 kHz, 2.5 kHz and 3.4 kHz. In a first series of experiments the dependence of loudness on the spectral distribution is measured. Additionally, the dependence on the temporal structure of the sound is determined. The results confirm the integration of the partial loudnesses via pitch and the rating of the sound intensity over an RC element of 100 ms time constant. Finally, sound of spectral as well as of temporal structure is used. It is shown that, though an integration takes place, it is only complete via pitch. The measured results are interpreted qualitatively.

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